United States
Department of
Agriculture

Agricultural
Research
Service

Production
Research
Report
Number 184

Efficiency of Feed Utilization in Swine

A Review of Research and Current Applications

ABSTRACT

Bereskin, B., and N.C. Steele. 1985. Efficiency of Feed Utilization in Swine: A Review of Research and Current Applications. U.S. Department of Agriculture Production Research Report No. 184, 24 p.

A review of research on the efficiency of feed utilization in swine during the growing-finishing period is presented. The major conclusions include the following: Efficiency (E), expressed either as units of feed consumed (F) per unit of gain in weight (G), F/G, or as G/F, should be measured either from a starting age or starting weight of the pig to a standard final weight. Gain in weight should reflect body growth of lean tissue. Feed intake should reflect a standard diet or diet ingredients, such as protein or energy content or total digestible nutrients. Lean-type pigs are more efficient in feed utilization than fat-type pigs. Estimates of genetic and phenotypic parameters are presented. Alternative approaches to improve E are discussed. A recommended approach would be to evaluate and select breeding herd replacements on the basis of an index that includes direct measures of G and average backfat thickness (ABF) at a standard weight, plus E, included indirectly in deriving the selection index by use of genetic covariances of E with G and with ABF.

KEYWORDS: feed utilization efficiency, genetic and phenotypic parameters, selection criteria, swine

Copies of this publication may be purchased from the National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161.

ARS has no additional copies for free distribution.

Issued January 1986

ACKNOWLEDGMENTS

This study was undertaken with the approval and support of the North Central Regional Technical Committee (NC-103): Genetic Improvement of Efficiency in the Production of Quality Pork. The senior author is a member of the NC-103 Technical Committee, representing the USDA Beltsville Agricultural Research Center. Members of the NC-103 Technical Committee contributing significantly to this report were L.D. Young, NC-103 coordinator, and G.E. Dickerson, USDA Roman L. Hruska Meat Animal Research Center, Clay Center, NE; R.K. Johnson, University of Nebraska; L.L. Christian and M.F. Rothschild, Iowa State University; F.C. Gunsett, North Carolina A&T State University; D.R. Hagen, The Pennsylvania State University; and W.E. Rempel, University of Minnesota. Encouragement and support for this study by I.T. Omtvedt, NC-103 administrative advisor, also is acknowledged with appreciation. In addition, the authors acknowledge with appreciation the contributions of H.J. Mersmann and W.G. Pond, USDA Roman L. Hruska Meat Animal Research Center; E.T. Kornegay, Virginia Polytechnic Institute and State University, Blacksburg; and C.C. Calvert, USDA, Beltsville Agricultural Research Center. However, the contributions by the above-named persons do not necessarily imply their agreement with the conclusions and recommendations presented by the authors in this report.

CONTENTS

Introduction 1

Theoretical consideration 1

Effects of diet and other factors on efficiency 4

Estimates of phenotypic and genetic parameters 7
- Heritability 7
- Phenotypic and genetic correlations 8

Experimental results with alternative measures of efficiency 8

Discussion and recommendations 10
- Expected genetic gains 12
- Combined economic responses 13

Literature cited 15

Appendix 19
- Derivation of relative economic weights 19

EFFICIENCY OF FEED UTILIZATION IN SWINE: A REVIEW OF RESEARCH AND CURRENT APPLICATIONS

By: B. Bereskin and N.C. Steele[1]

INTRODUCTION

Traditionally, efficiency of feed utilization (feed conversion efficiency or feed efficiency, E) in swine has been expressed either as units of gross feed consumed (F) per unit of gross weight gain (G), F/G, or its reciprocal, G/F. However, new considerations have raised serious doubts about the adequacy of using gross weights of F and G to estimate E. For example, efforts are gaining acceptance in the United States to reward producers of lean-type pigs and to penalize producers of fat-type pigs by means of updated pork grading systems at the packer level. Contributing to incentives for these efforts are changing life styles and dietary practices in this country and elsewhere in the world that have increasingly emphasized the need, mainly for reasons of bodily health, to consume lean meats and to avoid animal fats.

To encourage the efficient production of lean pigs, changes in evaluating E are being considered. These changes include designating G in terms of lean tissue growth and F in terms of feed nutrient composition. Alternatively, several studies, such as those by Robison and Berruecos (1973b) and Sather and Fredeen (1978), have suggested that selecting on the basis of an index of gross average daily gain during a standard test period and average backfat thickness at the end of the test period should result in essentially as much improvement in E as that obtained by selecting directly on E and would eliminate the need to measure feed consumption.

[1] Research animal geneticist and research leader, respectively, Nonruminant Animal Nutrition Laboratory, Beltsville Agricultural Research Center, Agricultural Research Service, USDA, Beltsville, MD 20705.

This review of mainly North American research on the efficiency of feed utilization in swine will be restricted to the growing - finishing period of the pig's life cycle. In addition, current applications and recommendations will be presented.

THEORETICAL CONSIDERATIONS

Expectations and interpretation of various measures of E have been widely discussed in the literature. Headly et al. (1961) reported that G and E in pigs conformed to the "law of diminishing returns." For example, pigs made decreasing gains per unit of feed consumed as they increased in live weight from 34 to 91 kg. The calculated "instant" efficiency (E = G/F) decreased linearly with increasing pig weight. They also found, however, that feed consumption increased with increasing pig weight such that the amount of feed available for growth after allowance for maintenance requirements was quite constant. As a result, values for G/F based on feed available for growth were largely uniform. These findings suggest that measures of E adjusted for maintenance needs of pigs would differ widely from those not adjusted for maintenance.

Magee (1962) showed statistically that for pigs which consume more feed, to be more efficient, the regression of G on F must exceed the value of E (=G/F) for the average of the pigs in the lower end of the scale in feed consumption. He concluded that breeders cannot improve E simply by selecting pigs with larger appetites and faster gains but, rather, must select on E, directly.

Koch et al. (1963) proposed that E measured as plus or minus the deviation of the linear regression of G on F is a more meaningful expression of the cause and effect relationship between G and F. They also proposed that the

maintenance needs could be accounted for by adjusting the feed data for the average test weight of the pig. However, Sutherland (1965), in a theoretical study, criticized this proposal, claiming that the deviation does not indicate the feed consumption required to produce a given gain. He concluded that the ratio F/G is a valid estimate of efficiency in testing and selection programs.

Park (1965) noted that only two independent variables are included among G, F, and E. He evaluated the relationships among these variables in tests with pigs growing over the interval between two specified weights (weight-constant interval) and between two specified ages (age-constant interval). In the weight-constant interval, fast-growing pigs required less time than slower growing pigs to reach a given weight. The reduced maintenance time tended to reduce F/G. With the age-constant interval, faster growing pigs go through a later stage of their growth cycle when they require more feed for maintenance due to their heavier body weight and for the deposition of more fatty tissue than slower growing pigs. Finally, he noted that age-constant intervals are impractical for evaluating E, as market pigs are sold on a weight basis.

Robison and Berruecos (1973a) measured F/G and G/F over a weight-constant interval (45.5 to 93.5 kg), over an age-constant interval (76 to 130 d), and over an interval between a specified age and a specified weight (76 d to 93.5 kg) (age-to-weight-constant). Average backfat thickness (ABF) was measured at 93.5 kg. F/G and G/F were evaluated either with an adjustment for maturity and/or for maintenance or body composition (ABF) or with no adjustment for these effects. Maturity was adjusted for by use of a covariate for age of the pig at the start or middle of the test. Maintenance was adjusted for by use of a covariate for weight of the pig at the start or middle of the test. Based on heritability (h^2) estimates and coefficients of variation, the authors concluded that F/G would be a more responsive measure of E than G/F and that use of the age-to-weight-constant or weight-constant interval was preferable to use of the age-constant interval. Adjustments for maturity and/or maintenance resulted in slightly lower estimates of h^2 for F/G and G/F. Also, correction for ABF slightly increased h^2 for F/G. These results suggest that efficiency of lean tissue production may be slightly more heritable than gross efficiency but that, because of lower estimates of h^2, correcting E for maintenance needs would not increase the response to direct selection for E. However, in any one selection group, the same animals would be selected regardless of which measure of E, F/G or G/F, was the criterion used.

Lasley (1977) reported the results of performance tests conducted with over 6,000 gilts by a commercial swine breeding company. Littermate or half-sister gilts averaging 23 kg in weight were fed in groups of three or four until they reached 91 or 100 kg. The relationships of F/G and probe ABF to ADG (average daily gain in weight) were both curvilinear. He found that selection on ADG would result in ABF increasing at an ever-increasing rate and F/G improving (decreasing F/G), but at an ever-decreasing rate. Selection for low ABF would elicit relatively weak responses in F/G and ADG. Selection for improved F/G would produce favorable responses in both ADG and ABF. Selection on increased appetite (increased F) would improve ADG, but at a decreasing rate, while ABF would increase at a faster rate. F/G would first improve but then become less efficient as ADG increased. Lasley concluded that these curvilinear relationships would result in changing heritabilities and genetic correlations for the traits in question. As a result, selection criteria to maximize genetic improvement should be periodically appraised and adjusted as necessary.

Gunsett (1984) noted that because F/G is a ratio, it has attendant problems for selection. He developed equations to

express F/G as a linear index (I) of F and G, with the result that the economic weights became functions of the trait means. He also developed equations to maximize genetic gains in F/G by using an index that requires direct measures only of G and ABF but incorporates the estimated genetic covariance of F with G and ABF. However, application of these indexes in actual swine testing practices has not been evaluated to date.

Gunsett (personal communication, 1984) also noted that in evaluating E on a weight-to-weight basis, G becomes a measure of days on test (D). The linear index dealing with the reduction in F, D, and ABF then becomes $I_E = b_F F + b_D D + b_{ABF} ABF$, where b values are partial regression coefficients.

Fowler et al. (1976) noted that the objective in future pig production will be to produce lean meat as efficiently as possible. The problem is in determining what part of the improvement in efficiency should be made by technological means (mainly related to management) and what part by selection. They discussed ways of determining selection criteria, one using the classical form of selection index construction (selection index model) and the other taking a more integrated view of the biology of pigs and technology of pig production (biological model). They criticized the selection index model mainly because it describes genetic improvement in terms of increased profitability of the pig within a narrow set of production and marketing situations.

Alternatively, the biological model attempts to improve the value of the pig as a meat-producing animal through changes that may be either genetic or technological. The authors (Fowler et al., 1976) recommended lean tissue feed conversion (LTFC) as the main criterion for selection in a biological model, with lean tissue growth rate (LTGR) as a secondary criterion for selection.

The authors discussed in some detail the various complex physiological factors that could affect LTFC. They concluded that the major factors are (1) the amount of fat deposition per unit of lean tissue gain (mainly controlled technologically by feed intake) and (2) LTGR. They discussed various ways LTFC could be improved by combinations of selection and technology. Technologies recommended were mainly restricted feeding or semi-ad libitum feeding. Restricted (or scale) feeding allows a constant percentage of estimated ad libitum feeding, depending on pig weight. Semi-ad libitum (or to-appetite) feeding allows the pig to eat what it will consume in a fixed interval, such as in 20 or 30 minutes, usually fed twice a day.

Smith and Fowler (1978) commented on the ideas presented by Fowler et al. (1976) and noted that current pig improvement schemes (in Great Britain) based on the selection index model appear to be effective in improving LTFC and LTGR. They agreed that recent advances in nutrition and physiology are promoting an increased understanding of underlying pig biology and allowing predictions about the joint effects of selection criteria, feeding systems, and other factors in pig improvement efforts. Possible deficiencies in the biological model are that (1) no allowance is made for possible changes in the relative economic values of lean tissue and feed and (2) no allowance is made for other traits, such as meat quality.

Smith and Fowler (1978) also noted that genetic trends in British station-tested pigs of the Large White and Landrace breeds indicated favorable changes in LTGR and LTFC. Pigs were tested on to-appetite hand feeding regimes, with index selection basically for LTFC. At the same time in both breeds, a correlated reduction in feed intake was noted. It averaged -.51 percent of the mean value per year and was in line with the biological model of Fowler et al. (1976).

Fredeen (1980) pointed out the absence of unequivocal scientific evidence bearing on the relative merits of ad libitum vs. some form of restricted

feeding for the detection of genetic differences in LTGR or LTFC. He added that one assumption in all forms of limit-feeding is that appetite and rate of ingestion are synonymous. As compared with lower rates of ingestion, pigs with a high rate of ingestion will appear to have a larger appetite, will tend to have a faster growth rate, and will tend to have a larger energy surplus from each meal for uses other than maintenance and protein synthesis. Thus, it seems inevitable that selection for lean tissue content under limit-feeding will discriminate against pigs with a high rate of ingestion. However, genuine ad libitum feeding, by permitting individual variation in frequency and duration of feeding times, places no premium on rate of ingestion. Daily intake thus becomes a truer expression of appetite, and selection for lean growth rate should not result in a reduction of daily intake. As a result, Fredeen contended that testing programs that place a premium on rate of ingestion, for example, to-appetite or scale feeding, may be less suitable for measuring genetic differences in LTFC than in programs based on ad libitum feeding.

Fredeen also noted that a crucial challenge facing the swine industry is whether the genetic stocks selected under high energy dietary regimes will be suitable for efficient use of lower energy diets. In recent decades the trend has been toward increased energy content of pig diets. According to Fredeen, reversal of this trend seems inevitable and preparation for it is long overdue. He noted unpublished results from Swedish research that pigs fed reduced density diets (reduced concentrations of energy and protein) had no different growth rates, greater lean tissue deposition, and superior LTFC than pigs fed higher density diets. Fredeen urged that this type of diet control under ad libitum feeding be given serious consideration by swine breeders.

Tess et al. (1983), in a computer simulation study of farrow-to-market swine enterprises, concluded that marketing hogs by age instead of by weight would significantly affect selection goals for producers. The importance of gross or lean growth rates would be increased because faster growing pigs would market more gross or lean weight than slower growing pigs in the same amount of time and for the same total nonfeed overhead costs. As a result, they claimed that greater genetic improvement in overall economic efficiency would be possible. However, this system would result in some hogs that are too leavy to command a premium price for the producer. Moreover, it is doubtful that producers will switch to a system of marketing hogs by age instead of by weight.

The main conclusions from all the previously discussed studies are as follows: (1) Efficiency should be measured either from a starting age or starting weight to a standard final weight; (2) estimates of E should contain some adjustment for differences in initial, midterm, or final weights; (3) gain in body weight should reflect body composition, primarily lean tissue growth during the test period; (4) for comparisons among animals tested under different diets, feed intake should reflect content of critical ingredients such as protein, energy, or TDN, rather than simply gross intake; (5) possibly important curvilinear relationships among the component traits in E would require periodic appraisal and adjustment of selection criteria; (6) statistical and biological problems inherent in selecting directly on the basis of a ratio such as F/G may favor use of a linear association of the components and related traits, such as ABF, in the form of a selection index; (7) improving LTFC should be a primary selection objective; and (8) reduced density diets need to be further evaluated under ad libitum feeding regimes as a means of improving LTFC.

EFFECTS OF DIET AND OTHER FACTORS ON EFFICIENCY

Numerous studies have been published on the effects of dietary differences on gross E in swine. The general result

that gross E improved with increasing levels of protein and/or energy levels in the diet was noted in trials conducted by the following researchers: Clawson et al. (1962), Wagner et al. (1963), Seymour et al. (1964), Jurgens et al. (1967), Hale and Southwell (1967), Luce et al. (1976), Bereskin et al. (1976), and Christian et al. (1980). In some of these trials, diets with different levels of protein were fed during the entire test period; in other trials, diets differing in protein content were fed in different sequences during the test period and the results compared. Protein levels varied from extremes of 10 to 25 percent, but most were in the 12- to 20-percent range.

Stage of growing period also affected E. Luce et al. (1976) reported that E improved more with an increase in percentage of dietary protein during the test period from 24 to 56 kg than during the test period from 56 to 100 kg. Final test weight also affected E. Christian et al. (1980) reported that pigs fed to 91 kg had better E than pigs fed to 114 kg.

No significant interaction effects of level of protein x level of energy in the diet on E were noted by Wagner et al. (1963) or by Bereskin et al. (1975). Wagner et al. tested protein levels ranging from 13 to 25 percent and metabolizable energy levels from 2.1 to 3.6 kcal/g. Bereskin et al. tested protein levels of 14 and 20 percent and metabolizable energy levels of 3.2 and 3.6 kcal/g in the diets.

The effects on E of adding synthetic amino acids or other growth stimulants to the diet have also been investigated. Jurgens et al. (1967) tested diets containing 12 or 16 percent crude protein with or without 1 percent added lysine. The 16-percent diets produced lower ($P < .01$) F/G than the 12-percent diets, but addition of lysine had no significant effect with either level of protein. Bereskin et al. (1976) tested three diets: (1) 12 percent protein; (2) 16 percent protein; and (3) 12 percent protein fortified with lysine and methionine to 16 percent protein equivalence. Diets (2) and (3) produced lower ($P < .05$) F/G than diet (1), but diets (2) and (3) did not differ ($P < .05$) in effects on E. Hagsten et al. (1978) fed a diet fortified with 2 g of bambermycin (streptomycin-related chemotheraputic) per ton of feed, along with a control diet, to pigs from 35 to 95 kg. They reported improvement of 6 to 6.5 percent in E by the fortified diet over the control diet.

Different compensatory responses in pig performance tests resulting from pretest dietary restrictions have been reported. Meade et al. (1969) fed pigs ad libitum from 5.9 kg to 23.5 kg on diets with protein levels of 12 to 27 percent and then fed ad libitum all the pigs the same diet to 90.7 kg. They reported no significant compensatory effects of the pretest protein restrictions on postrestriction E. However, Wyllie et al. (1969), Zimmerman and Khajarern (1973), Hogberg and Zimmerman (1978), and Prince et al. (1983) all reported that during tests, various degrees of compensatory effects on E resulted ($P < .10$ to $P < .01$) when protein intake during the pretest period was restricted to varying intensity and/or duration. This type of compensatory response could significantly affect the performance at central testing stations by pigs receiving different pretest treatments at consignors' farms.

The effects of fat- and lean-type pigs on E were reported by Bereskin et al. (1975). Fat-type Duroc and Yorkshire pigs averaging 8.0 and 6.6 cm in ABF, respectively, at 80 kg had an F/G of 3.54 units, whereas the lean-type Durocs and Yorkshires averaging 3.3 and 2.9 cm in ABF, respectively, at 80 kg, had an F/G of 2.95 units ($P < .01$). Christian et al. (1980) also reported that "lean" crossbred pigs had a better E (lower F/G) than "average" (fatter) crossbred pigs.

Several experiments have specifically compared performance by different breeds and/or compared straightbreds with

crossbreds. Both the studies by Quijandria et al. (1970) and by Neville et al. (1976) showed that Duroc boars were more efficient ($P < .05$ or $P < .01$) in F/G than various other breeds tested at two central testing stations. Johnson et al. (1973) reported that Yorkshires were more efficient than Durocs or Hampshires, but they reported no significant advantage in E for crossbreds over straightbreds. Young et al. (1976) reported that crossbreds were more efficient than the average of the Duroc, Hampshire, and Yorkshire purebreds tested. Johnson et al. (1978) reported no significant differences in E between two-breed and three-breed crosses derived from Duroc, Hampshire, and Yorkshire purebreds and no significant maternal influence on E. Fahmy and Bernard (1972) reported a 5.5 percent heterosis for E in Yorkshire line crosses over straightbreds selected for E in one line and for an index of carcass traits in a second line. Johnson (1980) reported a pooled heterosis percentage of only 1.8 percent for E in a review of literature. Kuhlers et al. (1980) reported that F/G for crossbred pigs (from Landrace dams and by Duroc and Yorkshire sires) was .27 units lower ($P < .01$) than for straightbred Landrace pigs (7.3 percent heterosis).

From a review of pertinent research studies (Lush et al., 1939; Dickerson et al., 1946; Sierk et al., 1951; Johnson et al., 1973; Young et al., 1976; Kuhlers et al., 1977; Kuhlers et al., 1980), the average heterosis effects reported were 9.60, 4.64, and 3.98 percent for ADG, average daily feed intake (ADF), and F/G, respectively, in terms of percentage increases in performance of crosses of inbred or straightbred lines or breeds of pigs over their parents. Assuming that inbreeding effects are a mirror image of heterosis effects, one can expect small reductions in ADF and E and perhaps twice as large a reduction in ADG under inbreeding. Also, Willham and Craft (1939) reported that outbred pigs had significantly higher coefficients of digestibility than inbreds. Based on these findings, the primary effects of heterosis appear to be (1) to stimulate appetite, resulting in increased ADF, and (2) to enhance digestibility, resulting in improved F/G in outbreds over that in inbreds. The net effect appears to be cumulative, by increasing heterosis for ADG to a greater extent than for either ADF or F/G.

Various environmental conditions have been shown to affect E. Seymour et al. (1964) reported that pigs housed at 2.2°C required more ($P < .05$) feed per unit of gain in weight than pigs housed at 15.5°C. Bereskin et al. (1975) reported that when both average temperature and humidity were included as covariates in analyses of F/G, higher humidity lowered E (increased F/G) ($P < .01$) while the concurrent temperature effect was not statistically significant. Heitman et al. (1961) reported an improved E ($P < .01$) for growing-finishing pigs allowed 1.86 m^2/pig in floor space compared with .46 or .93 m^2/pig. Also, E was better ($P < .05$) for groups of 12 pigs per pen than for groups of 3 or 6 pigs per pen when allowed equal floor space. Randolph et al. (1981) reported that pigs allowed .33 m^2/pig in floor space were less efficient ($P < .05$) than pigs allowed .66 m^2/pig. No significant differences in E were noted for pigs grouped 5 or 20 pigs per pen with equal floor space per pig.

The reported effects of sex of pig on E have not been consistent. For example, Wagner et al. (1963) reported that boars were more efficient than gilts, which in turn were more efficient than barrows. However, Hale and Southwell (1967), Bereskin et al. (1975), and Christian et al. (1980) all reported no significant difference in E between barrows and gilts. Siers (1975) reported that boars averaged 7.5 percent more efficient than the average of barrows and gilts. Bayley and Summers (1968) reported no significant difference between boars and gilts in E, with both being more efficient than barrows. Bruner and Swiger (1968) reported that gilts were more efficient ($P < .01$) than barrows in gross weight gains.

The effects of restricted feeding of market pigs during their growing-finishing period were investigated by Cleveland et al. (1983). Three feeding levels were employed: twice daily feeding to appetite (AP), once daily feeding of 91 percent of appetite intake (AP 91), and once daily feeding of 82 percent of appetite intake (AP 82). Pigs were fed a 16-percent-protein corn-soybean-meal diet during the 105-d test period, starting at 83 d of age. Results showed reductions ($P < .05$) in gross feed intake per gross weight gain and in gross feed intake per unit lean gain ($P < .01$) during the test period for pigs on AP 91 as compared with pigs on the AP diet. Further slight improvement ($P > .10$) was noted for pigs on AP 82. However, ADG was 10 percent lower in pigs on AP 91 than in those on AP. Thus, gain was reduced and efficiency was improved by restricting feed intake, thereby affecting in opposite ways the economics of ad libitum and restricted feeding regimes. Economic implications will be considered further in a later section. At the present time, the vast majority of market pigs in the United States are fed ad libitum.

It is obvious from the studies discussed in this section that efficiency of feed utilization is an extremely complex trait--one that is subject to a myriad of diverse effects. However, the following conclusions appear reasonable: (1) Gross E is improved with increasing protein and energy content of the diet when the contents generally conform to guidelines recommended by the National Research Council; (2) addition of synthetic amino acids to diets low in natural sources of amino acids is advantageous for improving E, and changing production techniques can be expected to improve further the economics of synthetic amino acid supplementation; (3) lean-type pigs are generally more efficient than fat-type pigs; (4) breed differences in E are variable, depending largely on samples of the breeds tested; (5) generally, very low levels of heterosis can be expected for E with crossbred pigs; (6) extremes in temperature, excessive humidity, and severely restricted floor space can have negative effects on E; (7) boars are generally more efficient than either barrows or gilts, with the relative efficiency of gilts in comparison with barrows being more variable; and (8) restricting feed intake below ad libitum levels will generally improve E but will reduce ADG.

ESTIMATES OF PHENOTYPIC AND GENETIC PARAMETERS

Genetic analyses of E in swine have been conducted in only a handful of studies in North America over the past 50 years. The paucity of such studies is probably due, in part, to the extra costs and difficulties associated with monitoring and obtaining accurate feed consumption data for swine.

Heritability

Lush (1936), in a classic study of data from Danish progeny-testing stations, computed heritability (h^2) of F/G to range from .08 to .29, based on paternal and maternal half-sib correlations of litter averages. Dickerson (1947), based on a nested analysis of records for 746 pigs, reported an h^2 of .57 for F/G but concluded that his estimate was biased upwards by an unknown amount. Dickerson and Grimes (1947) analyzed data from an 8-year experiment in which pigs were selected on their F/G records. An h^2 of .26 was computed by the regression of progeny on the mean of their parents. Biswas et al. (1966) reported an h^2 of $.30 \pm .23$ for G/F, based on a sires component of variance of records for 185 individually fed pigs.

Bernard and Fahmy (1970) analyzed data from a 10-generation experiment in which selection in 1 line was based on F/G. From the sires component of variance, h^2 for F/G was estimated as .16, with a realized h^2 estimate of $.11 \pm .13$. Jungst et al. (1981) analyzed data from 642 individually self-fed boars in a 5-generation experiment with selection on F/G. Heritability of F/G, based on the sires component of variance, was $.12 \pm .17$, with a realized h^2 of $.09 \pm .08$. Webb and King (1983) tested some 1,600

pigs fed ad libitum in littermate groups over a period of 6 generations and reported a realized h^2 for F/G of .007 $\pm$ .088 units in response to direct selection for pen average F/G. Bereskin (1986), in a study of 1,869 purebred Duroc and Yorkshire gilts fed ad libitum in 703 pens of littermate groups representing 339 sires, reported an h^2 of .061 $\pm$ .217 for F/G computed from a paternal half-sib nested analysis of pen means. In all these genetic studies, pigs were fed from initial weights ranging from 15 to 30 kg to final weights ranging from 80 to 100 kg.

From these reports, h^2 for E is probably in the range of .05 to .30, but more likely in the range of .10 to .20, with a suggested composite point estimate of only .15. This estimate compares with .35, the h^2 value incorporated into selection indexes that are used in central swine testing stations in the United States, as recommended by the National Swine Improvement Federation (U.S. Department of Agriculture, 1981).

Phenotypic and Genetic Correlations

Presented in table 1 are reported phenotypic correlations (r_P) and genetic correlations (r_G) of E (=F/G or G/F) with ADG, ABF, and ADF. All r_P values, except as noted in the table, were computed as product-moment (Pearsonian) correlations. For the genetic correlations, Dickerson and Grimes (1947) estimated r_G of E with ADG from the covariance of progeny with the mean of their parents and associated variances. Vogt et al. (1963) estimated r_G of E with ADG from the covariance of dams with their progeny litter averages and sire components of variance. Robison and Berruecos (1973b), Bereskin (1986), and Biswas et al. (1966) estimated r_G of E with ADG, ABF, and ADF from sire components of covariance and variance. Estimated composite phenotypic and genetic correlations and related parameters are presented under "Discussion and Recommendations."

EXPERIMENTAL RESULTS WITH ALTERNATIVE MEASURES OF EFFICIENCY

Bereskin and Davey (1976) tested 128 barrows and gilts of a high-fat or low-fat line of Duroc or Yorkshire breeding fed ad libitum from 63 d of age to 100 kg. In addition to standard measures of ADG, ADF, and E (=G/F), the efficiency of lean gain (ELG) was computed as the estimated gain in weight of closely trimmed lean cuts during the test period (LC gain) divided by the weight of the total dietary protein consumed during the test period. Both low-fat lines were more efficient (higher G/F) than both high-fat lines ($P < .01$). Error line phenotypic correlations were also computed between ELG and the other traits shown in table 2. The tested model included the effects of breed, line, sex, dietary protein and energy levels, two-factor interactions, and the covariate, slaughter weight.

Kuhlers et al. (1977) tested 95 purebred and crossbred pigs of Poland or Yorkshire breeding individually fed ad libitum from 56 d of age to 92.5 kg. Three measures of efficiency were evaluated: (1) G/F, gross weight gain adjusted for differences in on-test weight over gross feed consumption adjusted for midtest weight; (2) G/TDN, gross unadjusted gain in weight over total digestible nutrients consumed; (3) G/P, gross unadjusted weight gain over digestible protein consumed. For each of these three measures of E, purebred Poland pigs ranked lowest, Yorkshires the next, and crossbreds the most efficient. Heterosis for the three measures of E ranged from 5.2 to 5.8 percent, thus indicating no difference in advantage of any of the measures of E with respect to resulting heterosis.

Robison and Berruecos (1973b) theoretically compared direct selection for E with selection for an index of ADG and ABF. They concluded that selection on the index would improve E faster than direct selection on E alone. Sather and Fredeen (1978) investigated the effects on E in barrows and gilts when selection was based on an index of ADG and ABF.

Table 1. Reported phenotypic correlations (r_P) and genetic correlations (r_G) of E (=F/G or G/F) with ADG, ABF, and ADF

Reported r value and source	Trait ADG	ABF	ADF
r_P, with E = F/G			
Siers (1975)	-.43	-	-
Bereskin et al. (1975)	-.40	-	.54
Bereskin et al. (1976)	-.44	-	.06
Drewry (1980)	-.32	.27	-
Bereskin (1986)	-.24	.21	.57
r_P, with E = G/F			
Magee (1962)	.24	-	-.39
Biswas et al. (1966)	.24	-.20	-.54
r_G, with E = F/G			
Dickerson and Grimes (1947)	-.78	-	-
Vogt et al. (1963)	-.22	-	-
Robison and Berruecos (1973b)	-.78 ± .19	.33 ± .51	-.31 ± .31
Bereskin (1986)	-.52 ± .86	.69 ± .31	-.52 ± 1.38
r_G, with E = G/F			
Biswas et al. (1966)	.63 ± .26	.06 ± .65	.20 ± .47

Table 2. Error line phenotypic correlations

Trait	Trait[1] G/F	% LC	LC gain	ELG
G	.53**	-.11	.90**	.24
G/F		.07	.59**	.66**
% LC			.18	.28*
LC gain				.46**

[1]See text for description of traits.
** P <.01, *P <.05.

Pigs were individually fed ad libitum from 56 d of age to 90 kg, when ABF was measured. In one line, selection was based on the index. A randomly selected control line also was maintained concurrently. After three generations of selection, genetic response to selection was measured as the deviation of records by the select line pigs from the mean of contemporary control line pigs and expressed in standard deviation units (SDU). Select line pigs averaged 1.51 SDU less ABF, .95 SDU higher ADG, and 1.07 SDU lower F/G than the controls (all, P <.01). The authors concluded that a simple index designed to improve lean tissue growth rate and consisting of ADG and ABF could secure substantial genetic and economic improvements in E. As a result, they contended, F/G need not be included in selection indexes in swine testing programs. However, the experiment did not compare responses to their index with responses to direct selection for E or with an index that included E.

Cleveland et al. (1983) tested select and control line barrows from 83 to 188 d of age, when they were slaughtered to obtain lean tissue content. Additional littermate barrows were slaughtered to establish initial body lean content. The select line pigs had been selected for six generations on an index of ADG and ABF, while control line replacements were selected largely at random. Test pigs were fed a 16-percent-protein diet. Select line barrows averaged .20 units less (P < .01) feed per unit of gross live weight gain and .66 units less (P < .01) feed per unit of body lean gain than control line barrows, along with concurrent improvement in ADG and ABF. Control line barrows averaged 3.32 units of F/G for gross body weight gain

and 5.73 units of F/G for body lean gain. The authors reported also that select line pigs needed an intake of 1.90 fewer ($P < .01$) Mcal of metabolizable energy per kilogram of lean gain than control line pigs. Control line pigs averaged an intake of 16.53 Mcal of metabolizable energy per kilogram of lean gain. The authors reported that selection for the index of ADG and ABF increased the daily maintenance requirements of the faster growing pigs. However, their trials were conducted from initial age to final age, which presumably would have resulted in increased final weights and higher maintenance costs for faster growers than if the test had ended at a specific standard weight.

This section described results with several alternative selection criteria used for improving E in swine. Measures of G included gross weight gain and estimates of body lean tissue during the test period. Measures of F included gross weight of feed consumed or weight of protein, metabolizable energy, or total digestible nutrients consumed. However, no consensus was indicated as to why a particular combination of G and F would be preferred. A common feature of the criteria for F was that each required an accurate record of gross feed intake or feed ingredient intake, an expensive and difficult task. One alternative selection criterion evaluated was an index of ADG and ABF, which eliminates the need to record feed intake. This criterion will be evaluated further in the next section.

DISCUSSION AND RECOMMENDATIONS

Researchers, breeders, commercial producers, and others in the industry are increasingly recognizing that gross feed efficiency, F/G, is no longer an adequate indicator of genetic or economic merit of swine. Instead, new alternative measures may need to be developed and used. In addition, economic incentives to reward producers of lean pork and penalize producers of fat-type pork by upgrading pork grading systems are being implemented at the packer level. As a result, breeders and producers will need to measure and select pigs for the breeding herd on the basis of lean growth and its efficiency rather than on gross weight gain and its efficiency.

Alternative approaches to improving the efficiency of lean growth have been proposed. One approach would require an estimate of lean growth during the test period instead of gross weight gain. It would also require feed consumed to be expressed either as total weight of a standard diet consumed during the test period or in units of a dietary component such as protein, energy, or total digestible nutrients consumed per unit of estimated lean tissue produced during the same period. This alternative would still require careful monitoring and recording of feed consumption data, with all the attendant problems noted previously. In addition, it would require the availability of prediction equations to accurately estimate the lean tissue content of pigs at the start and end of the test period.

Prediction equations to estimate lean content at the start of the test period were proposed by Brannaman et al. (1984) for pigs weighing 15 to 50 kg and by Prince et al. (1981) for pigs weighing 25 to 45 kg. Equations to estimate lean tissue in carcasses weighing 65 to 95 kg (90- to 130-kg live weight) were proposed by Fahey et al. (1977), Powell et al. (1983), and Grisdale et al. (1984), among others. However, most of these prediction equations include estimates of longissimus muscle area or depth for more accuracy, requiring special measuring instruments--basically, ultrasonic scanning devices. Equations consisting only of body weight and ABF are available but provide less accuracy in estimating lean tissue content. Brannaman et al. (1984) proposed a more complex prediction equation to estimate lean tissue content of the live animal at market weight. It requires measures of body weight, shoulder depth, ham width, last lumbar fat thickness, and ham fat thickness, and it would result in an R^2 of .84. An

alternative aproach to direct selection for lean growth would be to select on the basis of a multitrait performance (selection) index. One such index, previously proposed by Sather and Fredeen (1978), would include two traits, ADG during a standard test period and ABF measured at the end of the test period. Such an index was calculated and its correlated effect on E determined, based on the assumed composite parameter values in tables 3 and 4. These parameter values were arbitrarily determined by the authors from the reported estimates presented in table 1.

The standard matrix form was used to compute the partial regression coefficients for the indexes (I), P x B = G x A and B = P^{-1} x G x A, where P is the array of phenotypic variances (σ^2_P, table 3) and covariances (table 4), B is the vector of partial regression coefficients (b), G is the array of genetic variances (σ^2_G, table 3) and covariances (table 4), and A is the vector of relative economic weights in dollars. (See appendix for derivation of economic weights.)

$$\begin{array}{ccc} P & \times & B \\ \begin{bmatrix} .0040 & .004869 \\ .004869 & .0950 \end{bmatrix} & \times & \begin{bmatrix} b_{ADG} \\ b_{ABF} \end{bmatrix} \end{array}$$

$$\begin{array}{cccc} = & G & \times & A \\ = & \begin{bmatrix} .0010 & .002288 \\ .002288 & .0428 \end{bmatrix} & \times & \begin{bmatrix} 22.50 \\ -6.30 \end{bmatrix} \end{array}$$

Solving for B, b_{ADG} = 5.1373; b_{ABF} = 2.5597; and I1 = 5.1373 ADG - 2.5597 ABF, with σ_{I1} = .77457 units.

Adjusting σ_{I1} to a standard deviation of 20 units, I1 = 133 ADG - 66 ABF, with ADG in kg/d and ABF in cm.

Table 3. Assumed composite estimates of heritabilities (h^2) and both phenotypic (P) and genetic (G) standard deviations (σ) and variances (σ^2) for ADG, ABF, and E = F/G

Parameter	Trait[1] ADG	ABF	E
h^2	.25	.45	.15
σP	.0632	.3082	.26
σ^2_P	.0040	.0950	.0676
σ_G	.0316	.2067	.1007
σ^2_G	.0010	.0428	.01014

[1] ADG expressed in terms of kg/d; ABF, in cm; E, in units of feed/gain.

Table 4. Genetic correlations and covariances (underlined) and phenotypic correlations and covariances between ADG, ABF, and E = F/G[1]

Trait	ADG	ABF	E
		Correlations	
ADG		<u>.35</u>	<u>-.60</u>
ABF	.25		<u>.35</u>
E	-.35	.20	
		Covariances	
ADG		<u>.002288</u>	<u>-.001909</u>
ABF	.004867		<u>.007292</u>
E	-.005751	.016026	

[1] E values based on test period ending at standard fixed weight rather than a fixed age.

A second index would include a direct measure of E in the index, along with measures of ADG and ABF. Based on the assumed composite parameter values in tables 3 and 4, along with relative economic values for ADG and ABF shown with I1, above, and - $18.00 per unit increase in F/G, I2 would be computed as for I1, with the following result:

I2 = 160 ADG - 51 ABF - 25 E; σ_{I2} = 20 units.

A third index would indirectly incorporate F/G as a selection criterion along with ADG and ABF by means of estimated genetic covariances of E with ADG and ABF (Arboleda et al., 1976). A direct measure of E would not be required for this index, which would be computed as follows:

$$\underset{P}{\begin{bmatrix} .0040 & .004869 \\ .004869 & .0905 \end{bmatrix}} \times \underset{B}{\begin{bmatrix} b_{ADG} \\ b_{BF} \end{bmatrix}}$$

$$= \underset{G}{\begin{bmatrix} .0010 & .002288 & -.001909 \\ .002288 & .0428 & .007292 \end{bmatrix}} \times \underset{A}{\begin{bmatrix} 22.50 \\ -6.30 \\ -18.00 \end{bmatrix}}$$

Solving for B, b_{ADG} = 16.0931; b_{ABF} = -4.5028, and adjusting to σ_{I3} = 20 units, I3 = 214 ADG - 60 ABF.

Expected Genetic Gains

The expected genetic gain (Δ) in a trait can be expressed in terms of response to one standard deviation of selection pressure per generation applied directly to that trait. If the trait is E, for example,

$\Delta E = \sigma^2_{G(E)} / \sigma_{P(E)}$ = .01014/.26

= -.0390 units of E (F/G) per generation, with negative selection pressure on E. Values for $\sigma^2_{G(E)}$ and $\sigma_{P(E)}$ are taken from table 3.

The expected genetic gain in E when one standard deviation of selection pressure per generation is applied on another trait, for example, ADG, is calculated as follows, with values from tables 3 and 4:

$\Delta E = \text{CovG}(E, \text{ADG}) / \sigma_{P(ADG)}$

= -.001909/.0632 = -.0302 units of E

(F/G) per generation.

The expected genetic gain in E when one standard deviation of selection pressure per generation is applied directly on an index of several traits, for example, I1, is calculated as follows:

$\Delta E = \text{CovG}(E, \text{I1}) / \sigma_{P(I1)}$

$= \left[b_1 \text{CovG}(E,\text{ADG}) + b_2 \text{CovG}(E,\text{ABF})\right] / \sigma_{P(I1)}.$

$\Delta E = \left[133(-.001909) - 66(.007292)\right] / 20$

= -.03676 units of E (=F/G) per generation.

The expected genetic gains in each of the three traits, ADG, ABF, and E, as a result of one standard deviation of selection pressure applied to the different criteria are shown in table 5. Selection pressure applied directly on ADG or ABF alone resulted in the largest genetic gains in those two traits. But selection on I2 and I3 resulted in slightly larger genetic gains in E than direct selection pressure on E alone, -.0465 or -.0423 vs. -.0390 units of E. Selection on I1 was only slightly less effective in improving E, genetically, as direct selection pressure on E, -.0368 vs. -.0390. These results appear to be due mainly to the low assumed h^2 value for E (.15) and the relatively high assumed

negative genetic correlation of ADG with F/G (-.60, tables 3 and 4).

Combined Economic Responses

Taking the comparisons one step further, estimates in dollar values of the combined responses in the three traits to one standard deviation of selection pressure for the indicated criteria are presented in table 6. These values were computed by weighting the expected genetic gain in each trait (table 5) by its estimated relative economic value per unit of change due to selection. For example, the estimated composite dollar value in response to one standard deviation of selection on ADG was computed as follows:

Composite dollar value = .0158 x $22.50 +.0362 x (-$6.30) + (-.0302) x (-$18.00) = $.67.

The other values were computed similarly. The results (table 6) indicate that the largest expected composite dollar response was produced by selection on index I3, at $1.50. Following closely was I2 at $1.46 (97 percent of I3) and I1 at $1.44 (96 percent of I3). Estimated composite responses from single trait selection were $.67 (45 percent of I3) for ADG, $1.14 (76 percent of I3) for ABF, and $1.04 (69 percent of I3) for E. Selection on any of the three indexes would be expected to result in larger composite dollar responses than selection on any of the three component traits alone.

The results would appear to support the conclusions of Robison and Berruecos (1973b), Sather and Fredeen (1978), Jungst et al. (1981), and Cleveland et al. (1983) that direct selection for E may not be the most effective way to improve E. Instead, selecting on an index such as I2, if feed consumption can be measured accurately and economically, or on indexes such as I3 or I1, if a direct measure of feed consumption is not feasible or practical, would result in larger economic responses than selection on E alone, directly.

Neither I3 nor I1 requires the direct measurement of feed consumption by the test animals, an expensive process requiring extra labor to check and adjust self-feeders and collect and account for feed wastage on a regular basis. In addition, if feed wastage is not controlled or properly accounted for, the affected boars on test may be credited with biased performance

Table 5. Expected genetic changes in traits resulting from 1 standard deviation of selection on different criteria[1]

Criterion of selection[2]	Trait ADG	Trait ABF	Trait E = F/G
ADG alone (+)	+.0158	+.0362	-.0302
ABF alone (-)	-.0074	-.1389	-.0237
F/G alone (-)	+.0073	-.0280	-.0390
I1 (+)	-.0009	-.1260	-.0368
I2 (+)	+.0046	-.0817	-.0465
I3 (+)	+.0038	-.1039	-.0423

[1] See text for further explanation.
[2] Direction of selection in parentheses.

Table 6. Expected economic values resulting from 1 standard deviation of selection on different criteria; component and composite values[1]

Criterion of selection[2]	Component value ($) ADG	ABF	E = F/G	Composite values ($)
ADG alone (+)	+.3555	-.2281	+.5436	+$.67
ABF alone (-)	-.1665	+.8751	+.4266	+1.14
F/G alone (-)	+.1642	+.1764	+.7020	+1.04
I1 (+)	-.0202	+.7938	+.6624	+1.44
I2 (+)	+.1035	+.5147	+.8370	+1.46
I3 (+)	+.0855	+.6546	+.7614	+1.50

[1] See text for further explanation.
[2] Direction of selection in parentheses.

indexes. If desired, feed efficiency could still be measured and reported, but would not be included as a selection criterion.

Use of an index such as I3 would appear to be the preferred selection criterion in swine testing programs. Its use would reduce the cost of testing, simplify testing programs, more closely relate central station tests to on-the-farm tests, and achieve at least as much overall genetic improvement in the economic traits, ADG, ABF, and E, as by use of an index such as I2 that requires a direct measure of feed efficiency for the test group. In practice, ADG and ABF would best be expressed as positive or negative deviations from contemporary means of tested pigs of the same sex. Then, 100 would be added to the index so that no negative index values would result, with 100 then being the mean score for all pigs included in a contemporary test. In terms of kilograms/day for ADG and centimeters for ABF, I3 would be as follows:

$I3 = 100 + 214\,(ADG - \overline{ADG}) - 60\,(ABF - \overline{ABF})$, where $\overline{ADG}$ and $\overline{ABF}$ represent the mean ADG and mean ABF records, respectively, for all pigs included in a contemporary test.

All traits considered previously in this report were presented in metric measure. In terms of pounds per day for ADG and inches for ABF, I3 would be as follows:

$I3 = 100 + 97\,(ADG - \overline{ADG}) - 152\,(ABF - \overline{ABF})$, where $\overline{ADG}$ and $\overline{ABF}$ are as described for I3 in metric measure, above, except for being expressed in pounds per day and in inches, respectively.

It should be noted that if entire farrow-to-market swine enterprises are considered or if economic conditions for swine production change for other reasons, the relative economic weights may need to be revised (Tess et al., 1983). Also, all genetic and phenotypic parameter values presented here relate to ad libitum feeding, a standard practice in the production of market pigs in North America. Use of restricted feeding regimes likely would require revised parameter estimates and resultant indexes. Finally, use of an index such as I3, requiring accurate estimates of the genetic covariances of E with ADG and ABF, depends on further research to more precisely define those parameter values and apply them to swine testing programs.

LITERATURE CITED

Arboleda, C.R., D.L. Harris, and A.W. Nordskog. 1976. Efficiency of selection in layer-type chickens by using supplementary information on feed consumption. 1. Selection index theory. Theoret. Appl. Genetics. 48:67-72.

Bayley, H.S., and J.D. Summers. 1968. Effect of protein level and lysine and methionine supplementation on the performance of growing pigs: response of different sexes and strains of pigs. Can. J. Anim. Sci. 48:181-188.

Bereskin, B. 1986. A genetic analysis of feed conversion efficiency and associated traits in swine. Accepted for publication in J. Anim. Sci.

Bereskin, B., and R.J. Davey. 1976. Breed, line, sex and diet effects and interactions in swine carcass traits. J. Anim. Sci. 42:43-51.

Bereskin, B., R.J. Davey, and W.H. Peters. 1976. Genetic, sex and diet effects on pig growth and feed use. J. Anim. Sci. 43:977-984.

Bereskin, B., R.J. Davey, W.H. Peters, and H.O. Hetzer. 1975. Genetic and environmental effects and interactions in swine growth and feed utilization. J. Anim. Sci. 40:53-60.

Bernard, C., and M.H. Fahmy. 1970. Effect of selection on feed utilization and carcass score in swine. Can. J. Anim. Sci. 50:575-584.

Biswas, D.K., P.V. Hurt, A.B. Chapman, and others. 1966. Feed efficiency and carcass desirability in swine. J. Anim. Sci. 25:342-347.

Brannaman, J.L., L.L. Christian, M.F. Rothschild, and others. 1983. Live animal measurements for estimating muscle quantity in market hogs. J. Anim. Sci. 57(Suppl. 1):213.

Brannaman, J.L., L.L. Christian, M.F. Rothschild, and E. A. Kline. 1984. Prediction equations for estimating lean quantity in 15- to 50-kg pigs. J. Anim. Sci. 59(4):991-996.

Bruner, W.H., and L.A. Swiger. 1968. Effects of sex, season and breed on live and carcass traits at the Ohio swine evaluation station. J. Anim. Sci. 27:383-388.

Christian, L.L., K.L. Strock, and J.P. Carlson. 1980. Effects of protein, breed cross, sex and slaughter weight on swine performance and carcass traits. J. Anim. Sci. 51:51-58.

Clawson, A.J., T N. Blumer, W.G. Smart, Jr., and E.R. Barrick. 1962. Influence of energy-protein ratio on performance and carcass characteristics of swine. J. Anim. Sci. 21:62-68.

Cleveland, E.R., R.K. Johnson, R.W. Mandigo, and E.R. Peo, Jr. 1983. Index selection and feed intake restriction in swine. II. Effect on energy utilization. J. Anim. Sci. 56:570-578.

Dickerson, G.E., J.L. Lush, and C.C. Culbertson. 1946. Hybrid vigor in single crosses between inbred lines of Poland China swine. J. Anim. Sci. 5:6-24.

Dickerson, G.E. 1947. Composition of hog carcasses as influenced by heritable differences in rate and economy of gain. Iowa Agric. Exp. Stn. Res. Bull. 354, 34 p.

Dickerson, G.E., and J.C. Grimes. 1947. Effectiveness of selection for efficiency of gain in Duroc swine. J. Anim. Sci. 6:265-287.

Drewry, K.J. 1980. Growth, feed consumption and efficiency of tested boars. J. Anim. Sci. 50:411-417.

Fahey, T.J., D.M. Schaefer, R.G. Kauffman, and others. 1977. A comparison of practical methods to estimate pork carcass composition. J. Anim. Sci. 44:8-17.

Fahmy, M.H., and C. Bernard. 1972. Heterosis in crosses between three lines of Yorkshire swine selected for feed efficiency and carcass quality. Can. J. Anim. Sci. 52:444-447.

Fowler, V.R., M. Bichard, and A. Pease. 1976. Objectives in pig breeding. Anim. Prod. 23:365-387.

Fredeen, H.T. 1980. Pig breeding: current programs and future production requirements. Can. J. Anim. Sci. 60:241-251.

Grisdale, B., L.L. Christian, H.R. Cross, and others. 1984. Revised approaches to estimate lean of pork carcasses of known age or days on test. J. Anim. Sci. 58:335-345.

Gunsett, Fields C. 1984. Utilization of a linear index to select for traits defined as either a ratio or a product of two component traits. Monograph, 9 p. N.C. A&T State Univ., Greensboro.

Hagsten, I., R.J. Grant, G.E. Combs and R. O'Kelley. 1978. Effect of bambermycins on performance of growing-finishing swine. J. Anim. Sci. 47:1233-1238.

Hale, O.M., and B.L. Southwell. 1967. Differences in swine performance and carcass characteristics because of dietary protein level, sex and breed. J. Anim. Sci. 26:341-344.

Headley, V.E., E.R. Miller, D.E. Ullrey, and J.A. Hoefer. 1961. Application of the equation of the curve of diminishing increment to swine nutrition. J. Anim. Sci. 20:311-315.

Heitman, H., Jr., L. Hahn, C.F. Kelly, and T.E. Bond. 1961. Space allotment and performance of growing-finishing swine raised in confinement. J. Anim. Sci. 20:543-546.

Hogberg, M.G., and D.R. Zimmerman. 1978. Compensatory responses to dietary protein, length of starter period and strain of pig. J. Anim. Sci. 47:893-899.

Johnson, R.K. 1980. Heterosis and breed effects in swine. North Central Regional Pub. No. 262, 51 p. Univ. Nebraska, Lincoln.

Johnson, R.K., I.T. Omtvedt, and L.E. Walters. 1973. Evaluation of purebreds and 2-breed crosses in swine: feedlot performance and carcass merit. J. Anim. Sci. 37:18-26.

Johnson, R.K., I.T. Omtvedt, and L.E. Walters. 1978. Comparison of productivity and performance for two-breed and three-breed crosses in swine. J. Anim. Sci. 46:69-82.

Jungst, S.B., L.L. Christian, and D.L. Kuhlers. 1981. Response to selection for feed efficiency in individually fed Yorkshire boars. J. Anim. Sci. 53:323-331.

Jurgens, M.H., D.B. Hudman, C.H. Adams, and E.R. Peo, Jr. 1967. Influence of a dietary supplement of lysine fed at two levels of protein on growth, feed efficiency and carcass characteristics of swine. J. Anim. Sci. 26:323-327.

Koch, R.M., L.A. Swiger, D. Chambers, and K.E. Gregory. 1963. Efficiency of feed use in beef cattle. J. Anim. Sci. 22:486-494.

Kuhlers, D.L., A.B. Chapman, and N.L. First. 1977. Estimates of genotype x environment interactions within and between two breeds of swine for production and carcass traits. J. Anim. Sci. 44:549-556.

Kuhlers, D.L., S.B. Jungst, and R.L. Edwards. 1980. Performance of Landrace, Yorkshire and Duroc sired pigs from Landrace sows. J. Anim. Sci. 50:604-609.

Lasley, E.L. 1977. Animal breeding--now and in the future. J. Anim. Sci. 44:307-310.

Luce, W.G., R.K. Johnson, and L.E. Walters. 1976. Effects of levels of crude protein on performance of growing boars. J. Anim. Sci. 42:1207-1210.

Lush, J.L. 1936. Genetic aspects of the Danish system of progeny-testing swine. Iowa Agric. Exp. Stn. Res. Bull. 204. 90 p.

Lush, J.L., P.S. Shearer, and C.C. Culbertson. 1939. Crossbreeding hogs for pork production. Iowa Agric. Exp. Sta. Bull. 380. 34 p.

Magee, W.T. 1962. Relationship between daily feed consumption and feed efficiency. J. Anim. Sci. 21:880-882.

Meade, R.J., L.D. Vermedahl, J.W. Rust, and D.F. Wass. 1969. Effects of protein content of the diet of the young pig on rate and efficiency of gain during early development and subsequent to 23.5 kg, and carcass characteristics and composition of lean tissue. J. Anim. Sci. 28:473-477.

National Hog Farmer. 1984. Lean hogs get bigger premium. Nat. Hog Farmer 30(5):46-51.

Neville, W.E., Jr., O.M. Hale, L.W. Grimes, and W.C. McCormick. 1976. Evaluation of performance and their time trends in three breeds of performance tested boars. J. Anim. Sci. 43:13-19.

Park, Y.I. 1965. Age-constant feed efficiency of pigs. J. Anim. Sci. 24:819-822.

Powell, S.E., E.D. Aberle, and R.D. Arthur. 1983. Prediction of percentage muscle in pork carcasses. J. Anim. Sci. 57:1392-1396.

Prince, T.J., D.L. Kuhlers, S.B. Jungst, and others. 1981. Prediction equations for estimating the quantity of muscle in 25- to 45-kg pigs. J. Anim. Sci. 53:663-665.

Prince, T.J., S.B. Jungst and D.L. Kuhlers. 1983. Compensatory responses to short-term feed restriction during the growing period in swine. J. Anim. Sci. 56:846-852.

Quijandria, B., J.R. Woodard, and O.W. Robison. 1970. Genetic and environmental effects on live and carcass traits at the North Carolina swine evaluation station. J. Anim. Sci. 31:652-655.

Randolph, J.H., G.L. Cromwell, T.S. Stahly, and D.D. Kratzer. 1981. Effects of group size and space allowance on performance and behavior of swine. J. Anim. Sci. 53:922-927.

Robison, O.W., and J.M. Berruecos. 1973a. Feed efficiency in swine. I. A comparison of measurement periods and methods of expressing feed efficiency. J. Anim. Sci. 37:643-649.

Robison, O.W., and J.M. Berruecos. 1973b. Feed efficiency in swine. II. Predictions of efficiency and genetic correlations with carcass traits. J. Anim. Sci. 37:650-657.

Sather, A.P., and H.T. Fredeen. 1978. Effect of selection for lean growth rate upon feed utilization by the market hog. Can. J. Anim. Sci. 58:285-289.

Seymour, E.W., V.C. Speer, V.W. Hays, and others. 1964. Effects of dietary protein level and environmental temperature on performance and carcass quality of growing-finishing swine. J. Anim. Sci. 23:375-379.

Sierk, C.F., and L.M. Winters. 1951. A study of heterosis in swine. J. Anim. Sci. 10:104-111.

Siers, D.G. 1975. Live and carcass traits in individually fed Yorkshire boars, barrows and gilts. J. Anim. Sci. 41:522-526.

Smith, C., and V.R. Fowler. 1978. The importance of selection criteria and feeding regimes in the selection and improvement of pigs. Livestock Prod. Sci. 5:415-423.

Sutherland, T.M. 1965. The correlation between feed efficiency and rate of gain, a ratio and its denominator. Biometrics 21:739-749.

Tess, M.W., G.L. Bennett, and G.E. Dickerson. 1983. Simulation of genetic changes in life cycle efficiency of pork production. III. Effects of management systems and feed prices on importance of genetic components. J. Anim. Sci. 56(2):369-379.

U.S. Department of Agriculture. 1981. Guidelines for uniform swine improvement programs. U.S. Dept. Agric. Program Aid 1157, 20 p.

Vogt, D.W., R.E. Comstock, and W.E. Rempel. 1963. Genetic correlations between some economically important traits in swine. J. Anim. Sci. 22:214-217.

Wagner, G.R., A.J. Clark, V.W. Hays, and V.C. Speer. 1963. Effect of protein-energy relationships on the performance and carcass quality of growing swine. J. Anim. Sci. 22:202-208.

Webb, A.J., and J.W.B. King. 1983. Selection for improved food conversion ratio on ad libitum group feeding in pigs. Anim. Prod. 37:375-385.

Willham, O.S., and W.A. Craft. 1939. An experimental study of inbreeding and outbreeding swine. Okla. Agric. Exp. Stn. Tech. Bull. 7, 43 p.

Wyllie, D., V.C. Speer, R.C. Ewan, and V.W. Hays. 1969. Effects of starter protein level on performance and body composition of pigs. J. Anim. Sci. 19:433-438.

Young, L.D., R.K. Johnson, I.T. Omtvedt, and L.E. Walters. 1976. Postweaning performance and carcass merit of purebred and two-breed cross pigs. J. Anim. Sci. 42:1124-1132.

Zimmerman, D.R., and S. Khajarern. 1973. Starter protein nutrition and compensatory responses in swine. J. Anim. Sci. 36:189-194.

APPENDIX

Derivation of Relative Economic Weights

ADG (average daily gain in pig weight): A .1-lb increase in ADG would save about 6 d on test in a pig weight gain of 200 lb (such as from 30 to 230 lb on test). Assuming nonfeed costs per pig of $.17/d (Dr. Maynard Hogberg, Michigan State University, personal communication), this savings is worth 6 x $.17, or $1.02/pig, or $10.20/lb (pound) increase in ADG, or $22.50/kg increase in ADG.

BF (average backfat thickness): Based on the Hormel hog buying program (National Hog Farmer May, 1984), a .2-inch increase in BF of a slaughtered hog would reduce the carcass value by one grade, or $2.00/cwt of carcass. A 1-inch increase in BF would result in a decrease in carcass value of 1.0/.2 = 5 x $2.00 = $10.00. Assuming a 160-lb carcass, the value of the carcass would be reduced by 1.6 x $10.00 = $16.00/inch increase in BF, or $6.30/cm increase in BF.

E (= F/G, total feed weight per total gain in weight): For F/G of 3.00, 600 lb of feed would be consumed to produce a gain of 200 lb. For F/G of 2.00, 400 lb of feed would be consumed to produce a gain of 200 lb, or a saving of 200 lb feed. At $9.00/cwt feed, $18.00 per unit decrease in F/G would be saved.